

Neutron Stars in Supernova Remnants
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Search for the Optical Counterparts of Southern Anomalous X-Ray Pulsars and Radio-Quiet Neutron Stars in Young Supernova Remnants

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Abstract. We report on our search for the optical counterparts of the Southern Hemisphere anomalous X-ray pulsar 1E1048.1-5937 and the radio-quiet neutron stars in supernova remnants Puppis A, RCW 103, and PKS 1209-52. The observations were carried out with the new MIT/CfA MagIC camera on the Magellan-I 6.5 m telescope in Chile. We present deep multiband optical images of the X-ray error circles for each of these targets and discuss the resulting candidates and limits.

1. Background

The anomalous X-ray pulsars (AXPs) are a group of X-ray pulsars whose spin periods fall in a narrow range ($\sim 6 - 12$ s), whose X-ray spectra are very soft, and which show no evidence that they accrete from a binary companion (see Mereghetti 1999 for a recent review). These objects may be isolated neutron stars with extremely strong ($\sim 10^{14}$ G) surface magnetic fields, or they may be accreting from a “fallback” accretion disk. Optical measurements could potentially help discriminate between these models. An optical counterpart to one AXP, 4U 0142+61, has recently been identified and shown to have peculiar optical colors (Hulleman et al. 2000).

The radio-quiet neutron stars (RQNSs) are a group of compact X-ray sources found near the center of young supernova remnants. Their X-ray spectra are roughly consistent with young, cooling neutron stars, but they show no evidence for the non-thermal emission associated with “classical” young pulsars like the Crab (see Brazier & Johnston 1999 for a review). The X-ray spectral properties of the RQNSs and the AXPs are similar (see, e.g., Chakrabarty et al. 2001). Below in Table 1, the general properties of the three RQNSs as our targets in the southern sky are listed.

2. Observations

Our observations were made using the Magellan Instant Camera (MagIC) on the Magellan-1/Walter Baade 6.5-meter telescope at Las Campanas Observatory, Chile. MagIC is a CCD filter photometer built by MIT and CfA for the $f/11$ focus of the Baade telescope. The current detector is a 2048×2048 SITe CCD with a 69 mas/pixel scale and a 142×142 arcsec field of view. We used the Sloan

Table 1. Radio-Quiet Neutron Stars

Source	SNR	d (kpc)	Age (10^3 yr)	kT_{bb} (keV)	Refs
1E 0820–4247	Pup A	2.0	3.7	0.28	1-3
1E 1614–5055	RCW 103	3.3	1-3	0.56	4-6
1E 1207–5209	PKS 1209–52	1.5	7	0.25	7-9

References. – (1) Petre et al. 1982. (2) Petre, Becker, & Winkler 1996. (3) Pavlov et al. 1999.

(4) Tuohy & Garmire 1980. (5) Caswell et al. 1975. (6) Gotthelf, Petre, & Hwang 1997. (7) Helfand & Becker 1984.

(8) Bignami, Caraveo, & Mereghetti 1992. (9) Mereghetti, Bignami, & Caraveo 1996.

filter set, which have the following central wavelengths (Fukugita et al. 1996): $u'=3540$ Å; $g'=4770$ Å; $r'=6230$ Å; $i'=7620$ Å; and $z'=9130$ Å.

Table 2. Magellan Observations

Source	Date	Exposure Time (min)				
		u'	g'	r'	i'	z'
1E 1048.1–5937	2001 Mar 24	...	...	10	10	10
1E 1207–5209	2001 Mar 24	...	10	9	10	10
	2001 Jun 12	5	...	...	...	...
1E 0820–4247	2001 Mar 25	...	...	10	10	6
1E 1614–5055	2001 Mar 25	...	...	10	10	10

3. Results

Puppis A and PKS 1209–52 As shown in Figure 1, no optical counterparts are found in our images within the error regions derived from *Chandra*/ACIS observations of these supernova remnants. (For PKS 1209–52, the *Chandra* observations were made in CC mode, so that only a 1-D position constraint is given: this is plotted as two parallel dashed lines in Fig. 1(b).) The upper limits on an optical counterpart for PKS 1209–52 are: $u' > 22.5$, $g' > 24.4$, $r' > 24.8$, $i' > 24.4$, and $z' > 22.9$. For Puppis A, the limits in r' and i' bands are similar to those for PKS 1209–52, and $z' > 22.4$.

1E 1048.1–5937 As *Chandra* has not observed this AXP yet, the error circle (from *EXOSAT*) is relatively large, $15''$. We are able to identify 41 stars in this region that are bright enough to be measured in r' , i' , and z' bands (see Fig. 2(a)). However, none of these stars has peculiar colors (see Fig. 2(b)). **RCW 103** No optical counterpart is detected in the $0.''54$ error circle derived from *Chandra*/ACIS observations. However, three faint stars are detected near the error circle ($< 2''.5$ away from the X-ray position), which we label as A, B, and C in Figure 3(a). Their magnitudes are shown below:

	r'	i'	z'
A	> 25.6	23.20 ± 0.15	21.56 ± 0.04
B	25.6 ± 0.3	22.22 ± 0.14	20.36 ± 0.02
C	23.8 ± 0.1	21.48 ± 0.13	19.94 ± 0.02

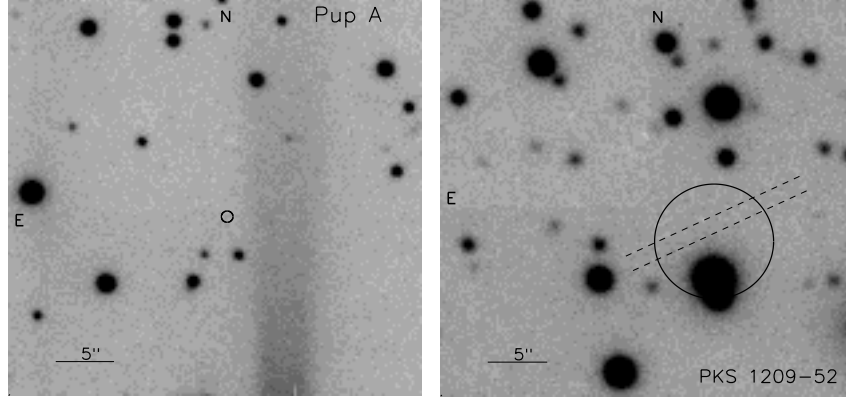


Figure 1. (a) Magellan MagIC image of Puppis A (1E 0820-4247) region in i' band. The X-ray source position, derived from the *Chandra*/ACIS observation, is indicated as a $1''$ diameter circle. (b) Magellan MagIC image of PKS 1209-52 (1E 1207-5209) region in i' band. A $5''$ circle indicates the X-ray source position given by *Einstein*/HRI observation (Seward 1990). Two parallel dotted lines with the width of $1''.4$ between them, which cross the HRI error circle, are drawn to indicate the position derived from *Chandra*/ACIS observation.

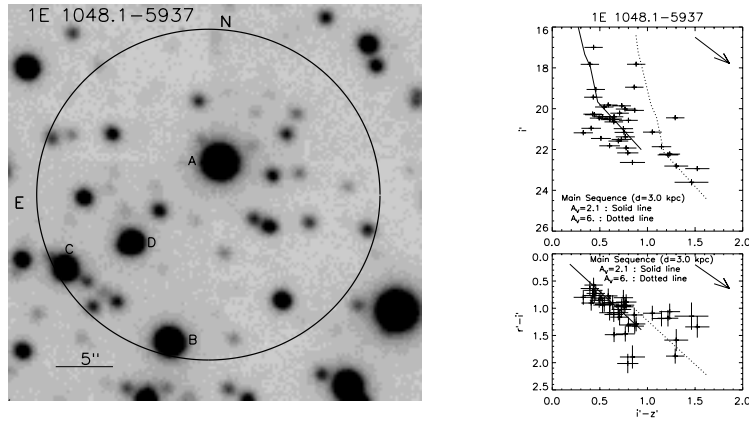


Figure 2. (a) Magellan MagIC image of 1E 1048.1-5937 region in i' band. A $15''$ circle indicates the X-ray source position given by EXOSAT/CMA observation (Mereghetti et al. 1992). Star A, B, C, and D are four stars measured by Mereghetti et al. (1992; see Figure 1 in their paper). (b) Color-magnitude and color-color diagrams for objects within the error circle of 1E 1048.1-5937 shown in (a). The solid lines and dotted lines indicate the main sequence with $A_V = 2.1$ and $A_V = 6$, respectively, both at a distance of 3 kpc. The arrows at the upper right corner show the reddening direction with $A_V = 2$.

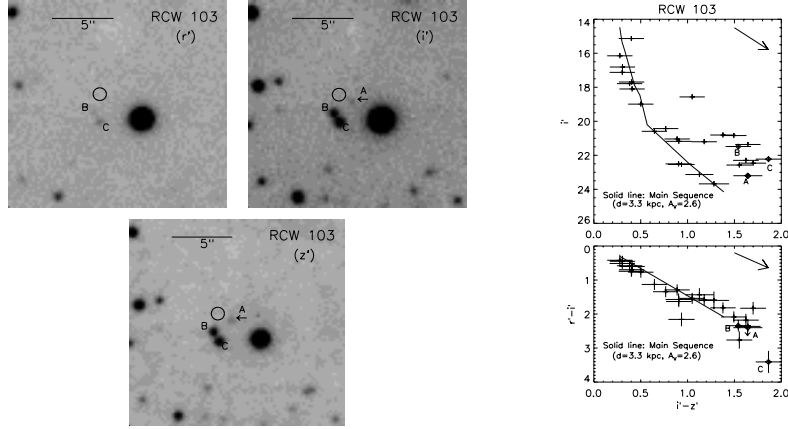


Figure 3. (a) Magellan MagIC images of the region around RCW103 (1E 1614-5055) in r' , i' , and z' band. The $0''.54$ circle indicates the X-ray position derived from *Chandra*/ACIS observation (Garmire et al. 2000). (b) Color-magnitude and color-color diagrams for objects near the X-ray source position of RCW 103. The solid lines indicate the main sequence with $A_V = 2.6$ at a distance 3.3 kpc. The star A, B, and C shown in Fig. 4(a) are labeled. For star A, the upper limit of the color $r' - i'$ is shown.

As shown in Figure 3(b), the colors of star B and C are normal which are consistent with those of reddened main sequence stars. Star A may be a normal star with extremely high extinction.

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